Downloaded from rsta.royalsocietypublishing.org

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Subsidence and Sea-Level Rise in the Thames Estuary

B. D'Olier

Phil. Trans. R. Soc. Lond. A 1972 **272**, 121-130
doi: 10.1098/rsta.1972.0038

Email alerting service Receive free email alerts when new articles cite this article - sign up in the box at the top right-hand corner of the article or click **here**

To subscribe to *Phil. Trans. R. Soc. Lond. A* go to: **http://rsta.royalsocietypublishing.org/subscriptions**

This journal is © 1972 The Royal Society

Downloaded from rsta.royalsocietypublishing.org

Phil. Trans. R. Soc. Lond. A. **272**, 121–130 (1972) [121]
Printed in Great Britain

Subsidence and sea-level rise in the Thames Estuary

By B. d'Olier
Thames Estuary Research Group, City of London Polytechnic,
Jewry Street, E.C. 3

The development of the area of the Thames Estuary is briefly traced since the late Cretaceous period, with its present outline being due to a combination of factors. The overall subsidence of the North Sea area, the 'Alpine' fold movements, and the transgression of the sea since the retreat of the Weichselian ice-sheets have all contributed. The positions of the shore-line during the critical phase, 9600 B.P. to 8000 B.P., of this last transgression of the sea are shown. Subsequent to this main transgressive phase, erosion of the shoreline has been rapid due to storm-waves and tidal current action. An estimation of the average rate of subsidence and/or sea-level rise is given based on the concept of sedimentary equilibrium in which a figure of 12.7 cm (5 in) per century is arrived at.

Introduction

Although a study of the problem of subsidence and eustatic change in southeastern England was not intended as a primary objective of the research programme when the latter was initiated, it became obvious as the work progressed that important contributions to the understanding of these complex phenomena might result.

The research project was started as a team study of the structural framework, the sediments and recent sedimentary processes acting within the Thames River and Estuary including a special study of these factors within the Medway River basin (Kirby 1969). The author chose to work on the most easterly section, the Outer Thames Estuary and a narrow adjoining part of the southern North Sea, in total, an area of some 2000 km^2 (figure 1), and the interpretations in this paper are based upon this work with some additional material provided by his research colleagues.

Structural setting

The area termed the Thames Estuary is in fact the drowned portion of the London tectonic basin (Prestwich 1850), the latter being a pitching synclinal structure opening out towards the northeast. This syncline parallels the essentially east–west nature of the Old Armorican thrust front that runs under the southern edge of the Thames Estuary area. Wooldridge & Linton (1955) develop the idea that the London Tectonic basin is really an expression of the underlying Palaeozoic structure and this basin with its relatively thin veneer of Cretaceous and Tertiary sediments was formed during three main phases of earth movements, during late Cretaceous and Tertiary times. The most important period of folding was that one reaching its climax during the late Oligocene and early Miocene periods. At the same time the structural pattern of the North Sea basin began to form with the axis of greatest subsidence running approximately parallel to its present west and east coasts. The conformity between this Tertiary basin and the present coastline is very marked and would imply that the shape of the present North Sea is almost entirely a Tertiary feature. It would appear therefore that the London Basin was not only a peripheral extension of this main subsiding North Sea Tertiary basin but, was brought into greater prominence by the effect of the mid-Tertiary earth movements.

The Royal Society is collaborating with JSTOR to digitize, preserve, and extend access to
Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences.
www.jstor.org

Downloaded from rsta.royalsocietypublishing.org

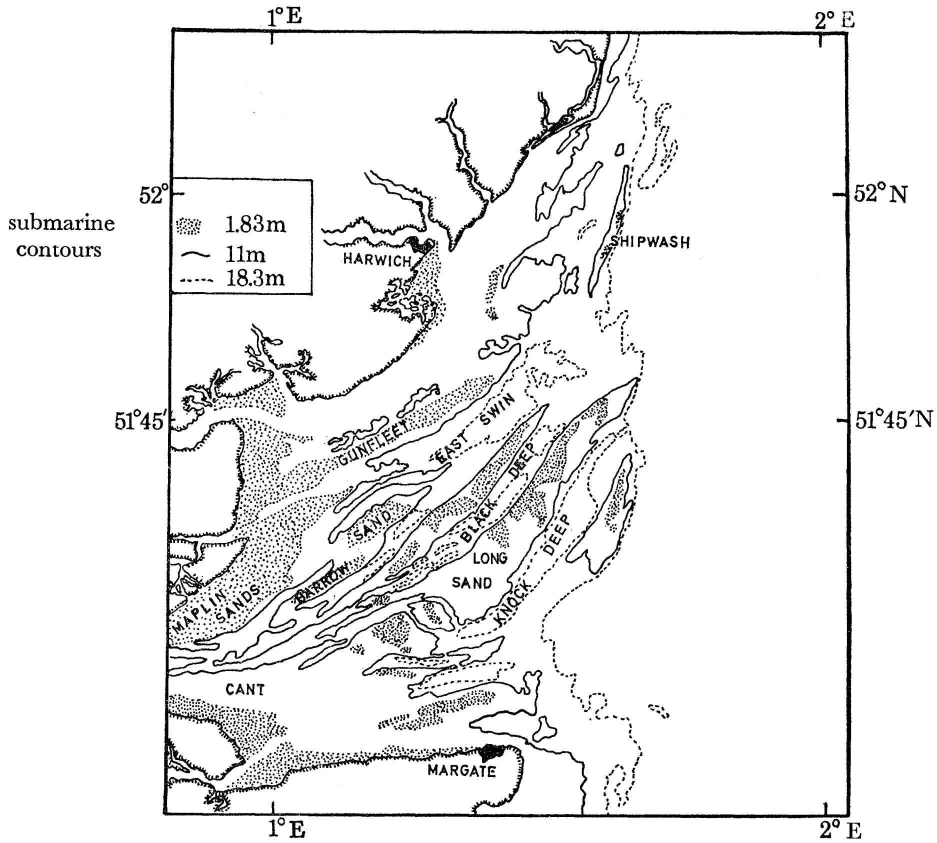

Figure 1. The Thames Estuary.

Recent subsidence

To exemplify this long established and recurrent tendency for the East Coast region and the Thames Estuary to be tilted towards the North Sea depression, basal Pleistocene deposits are found in Suffolk and Norfolk close to contemporary sea level. At Utrecht similar deposits are found at -320 m o.d., while these deposits are found at even greater depth -800 m o.d., towards the centre of the North Sea basin.

This subsidence appears to be continuing to this day, although the estimation of the rate of subsidence, so important in understanding the recent history of the outer estuary, is complicated by the eustatic and isostatic re-adjustment that the area has undergone, and is still undergoing, since the last ice-age. Other minor factors such as the compaction of sediments, often local and therefore variable in amount; and movements resulting from human activity, this latter being important where artificial lowering of the water-table causes shrinkage and settling, further complicate the ready understanding of the problem of subsidence. In peats a maximal compression and shrinkage ranging between 80 and 90 % of the original thickness can result (Jelgersma 1961), while in sands as little as 2 % may result (Athy 1930).

Recent sea-level variation

Sea-level fluctuation is the other major factor to be considered when dealing with land, sea relations in southeastern England. Eustatic change of sea level can be caused by changes in the form of ocean basins, from sediment accumulation displacing sea water, from changes in sea

Downloaded from rsta.royalsocietypublishing.org

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

temperature, local air pressure and wind flow variations but all of these have only a very minor effect. 'The fluctuations in the volume of the ice-sheets is believed to have had the greatest effect upon sea level' (Daly 1920). It has been calculated from measurements taken during the International Geophysical Year 1958, that if all the remaining ice melted, sea level would rise a further 61 m.

Chiefly from the study of submerged shore-lines, it has been variously suggested that, during the last ice-age, sea level was 160 m (Donn, Ferrand & Ewing 1962), 130 m (Stride 1959), or more commonly 100 m (Fairbridge 1962; Curray 1961), below its present level.

Penck & Bruckner (1909) defined four ice-ages during the Pleistocene period, and although there has been controversy as to the correct transposition of this subdivision from the classic area in the Alps to the more studied and better exposed deposits of Scandinavia, nevertheless it would seem probable that the area of the Thames Estuary has been exposed to subaerial denudation during each of these four periods. The sea levels during the first three glacial stages are unknown, although estimates suggest levels of between −100 to −130 m. In the Weichselian and during the ensuing Flandrian stage, changes have been estimated with far greater precision.

With the close of the Ipswichian interglacial stage, around 70000 B.P., cold conditions set in once more, resulting in a vast increase in the ice-sheets of the world with a consequent sea level fall to well over −100 m O.D. The greatest advance of the ice and presumably the lowest sea level occurred between 57000 and 42000 B.P., as established by the radio-carbon dating of organic materials from various river terraces (Godwin 1960). This was followed by a gradual warming, culminating in a short interstadial (Paudorf) at around 30000 B.P., evidenced by numerous radio-carbon dates of low arctic peat beds and also a high sea level indicated by shore-line deposits at −15 m O.D. Later there was a return to an intensely cold period in the Northern Hemisphere culminating in another very strong advance of the ice at around 17500 B.P. From that time there has been a retreat of the ice-sheets to the position they hold today, this retreat being marked by numerous ice-front oscillations with corresponding oscillations of sea level. Most workers in this field agree that sea level closely attained its present level about 5000 B.P. since when it has risen only slowly and slightly.

Early Holocene shorelines

Baak (1936) in subdividing the North Sea into five provinces based upon the petrology of the recent sediments, noticed that sediments around the Dutch Hinder group of sand-banks strongly resembled those described by Edelman (1933) for the rivers Rhine and Meuse. He therefore postulated that before the Flandrian transgressive phase the River Rhine–Meuse crossed the floor of the present North Sea in the vicinity of the Hinder banks and emptied into the Atlantic, having traversed the Dover Straits and part of the English Channel. He went on to state that 'The present North Sea floor represents an old land-surface only locally deformed by water action'. Jelgersma (1961) recognized this work and linked it with later work by Pons & Wiggers (1958) who described the course of these rivers across Holland at the end of the Pleistocene. She constructed a depth contour map of the southern North Sea, saw indications in these contours of the former river courses and proceeded to draw maps illustrating coastlines at different times during the early Holocene as the sea transgressed from the south. She assumed:

(1) Baak's hypothesis of the North Sea being a submerged land surface only locally deformed by recent marine erosive activity.

Downloaded from rsta.royalsocietypublishing.org

(2) That 'moorlog' samples taken from different depths in the present North Sea were all 'Lower Peat' samples laid down on the old land surface just above high-tide level. The decreasing age of these peats with decreasing depth below ordnance datum were taken as a chronology of the transgression (figure 2).

Jelgersma shows no marine incursion into the Thames Estuary during the period of time covered by her transgressive shoreline reconstruction, 9300 to 8300 B.P. This is essentially because she had no knowledge of the buried channel system of the area. In fact having no knowledge of those parts of the submerged land surface that lie buried by recent sediments, means, that in detail her maps lack precision.

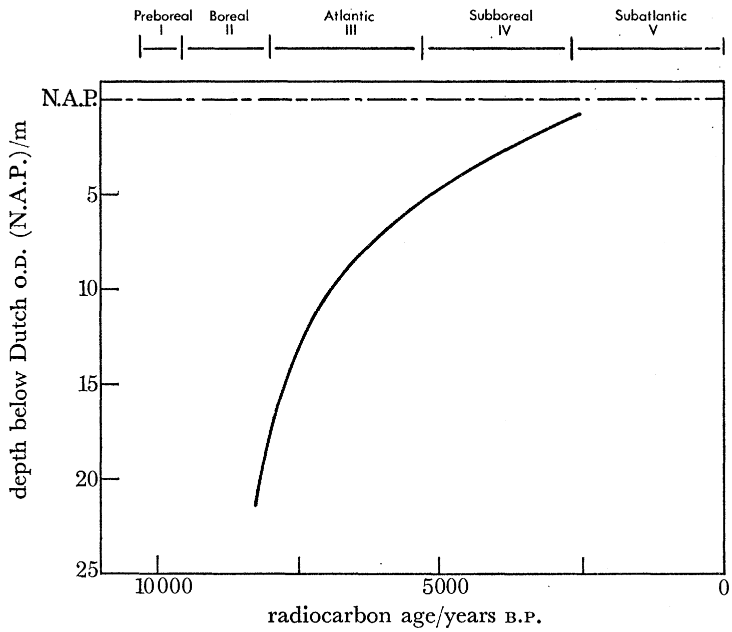

FIGURE 2. Time–depth graph (after Jelgersma 1961) with curve of relative changes in sea level. (Suess effect, 300 years, added to all dates.)

The author in attempting the reconstruction of similar maps to cover the whole of the Thames Estuary and the adjacent parts of the North Sea has however accepted Jelgersma's basic work pertaining to rate of sea-level rise and the concomitant subsidence of the southern North Sea. In constructing these shoreline maps detailed information obtained by use of the continuous reflexion seismic profiler has been used (figure 3); in all some 1385 km of subsurface profiling being used in the interpretations. In addition, evidence from some 40 boreholes, many drilled during the feasibility study for the projected Foulness airport–seaport complex, were used, one of them being drilled in a spot over which a seismic profile had been run. This allowed the speed of sound through the superficial sediment cover to be calculated, proving it to be 1570 m/s. This figure was subsequently used in all the seismic profiling interpretations. From this information a complete reconstruction of the now mostly buried bedrock surface could be carried out for the whole of the Thames Estuary area.

Over wide areas, covering this London Clay and in places Chalk surface is a layer of coarse flint gravel sometimes up to 1 m thick. This represents the coarser fraction of fluvial and fluvio-glacial origin, spread by the incoming sea over this land surface. Strangely over quite large areas no gravel is found and this is interpreted as indicating areas that were land at the end of the

Downloaded from rsta.royalsocietypublishing.org

main transgressive phase and have suffered subsequent coastal erosion by waves and tidal current action. No basal conglomerate is therefore present, only the finer material more recently distributed by tidal currents. It was found from seismic information that a maximum of 3 m and more usually 2 to $2\frac{1}{2}$ m has been removed from the channel areas between the present sand-banks. Although it was here where the greatest erosive activity might be thought to be

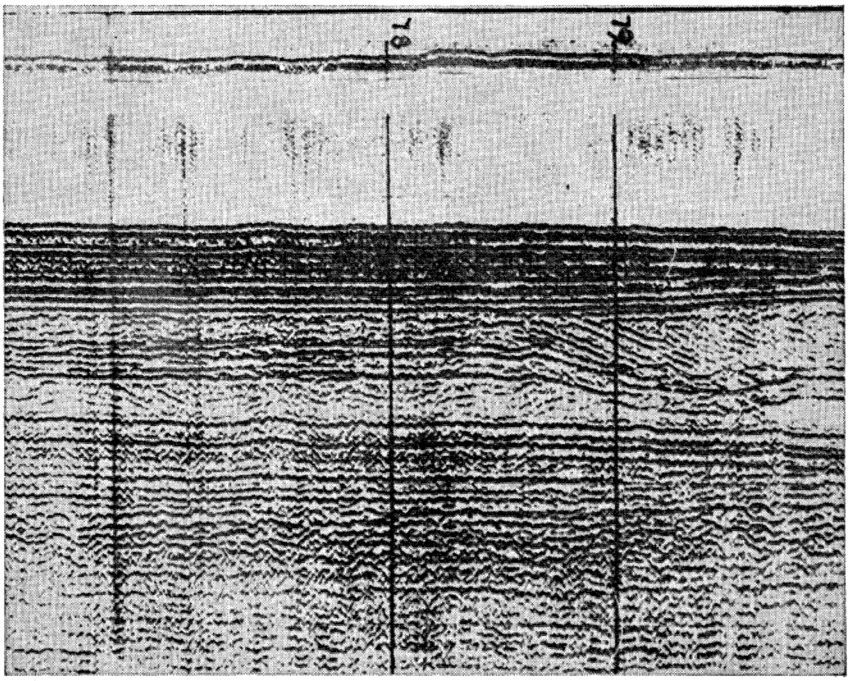

FIGURE 3. Continuous reflexion seismic record showing buried channel deposits.

taking place the bedrock is to a great extent protected by the gravel and shell deposits that are found there. The strong wave action of the very shallow transgressive sea would however remove not only any fluvial deposits that had been deposited but probably would have eroded some of the bedrock. As the surface of this bedrock is very likely to have been in a highly weathered state due chiefly to rain, frost and the action of percolating waters, the amount of initial erosion by the sea is likely to have been appreciable. The author has therefore assumed the removal of 2.5 m of bedrock over the whole of the bedrock surface during these early transgressive stages, before it became protected by a thick layer of sediment as the water deepened.

The shoreline maps therefore include the assumptions of Jelgersma with the additional factors as outlined above.

Shoreline of 9600 B.P.

Jelgersma (1961) does not show a map for this time, having no moorlogs of this age. Fairbridge (1958), Curray (1961) agree on sea level being between 43 and 47 m below O.D. at this time. The author has therefore accepted −45 m as being high tide level. Figure 4 shows that the sea advanced up through the Straits of Dover, along the wide flood-plain valley of the Rhine–Meuse–Thames river complex. To the north lay a wide land-bridge between Holland and the North Norfolk and Lincolnshire coasts. This sea advanced into the deepest sections of the Thames river complex while the rest of the area of the modern Thames Estuary was a relatively flat region covered by fluvio-glacial drift and flood-plain alluvium.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Downloaded from rsta.royalsocietypublishing.org

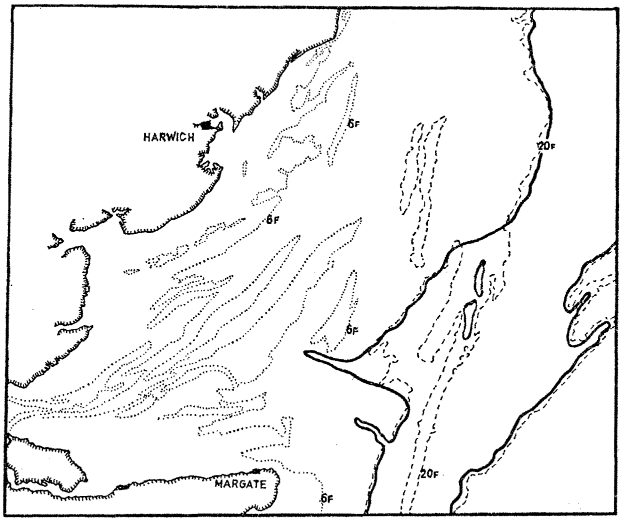

FIGURE 4. Position of the shoreline (—) about 9600 B.P.

Shoreline of 9300 B.P.

According to Jelgersma the sea at this time had reached a level of −40 m below present O.D. As such it had penetrated deeply up the now buried channels of the Thames–Medway–Crouch river complex and the Stour–Swale complex. According to Jelgersma the land-bridge still existed between England and Holland while to the north of this lay a northern sea.

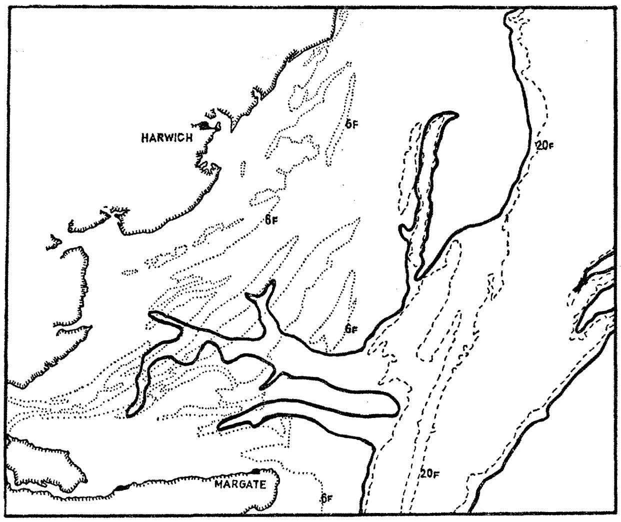

FIGURE 5. Position of the shoreline (—) about 9300 B.P.

Shoreline of 9000 B.P.

The high-tide level of this time is believed to have been at approximately the −34 m level. The river complexes were therefore more extensively flooded with the sea having penetrated nearly as far as Foulness point. The two north–south trending valleys some 32 km east of Harwich were completely flooded while to the north the land bridge to Holland was rapidly diminishing in area.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Downloaded from rsta.royalsocietypublishing.org

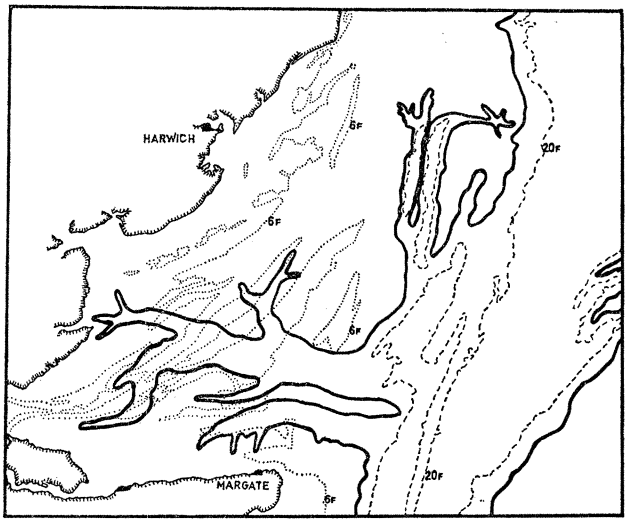

FIGURE 6. Position of the shoreline (—) about 9000 B.P.

Shoreline of 8600 B.P.

The high-tide level is believed to have been at −28 m O.D. at this time with the land bridge to the north having at last been partially overtopped (Jelgersma 1961). Numerous islands stood above the sea surface, while the sea had penetrated the old river valley system as far as Canvey Island and the Isle of Grain.

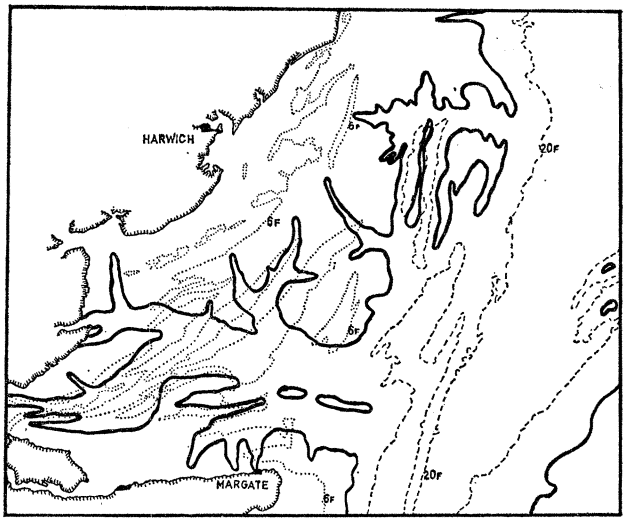

FIGURE 7. Position of the shoreline (—) about 8600 B.P.

Shoreline of 8300 B.P.

This period, when sea level reached the −22 m level saw the complete submergence of the old river valleys running across the present area of the Thames Estuary. Off the Isle of Thanet lay the remnants of the 'spine-land' that lay between the river complex of Thames, Medway and Crouch and that of the southern Stour and Swale. Much of the Foulness and Maplin Sands area was still dry land although the valleys of the Roach and Crouch were submerged. It is at this time that the sea began to invade the valley system of the Northern Stour, Orwell, Deben and

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Downloaded from rsta.royalsocietypublishing.org

Ore rivers. Carr & Baker (1968) mention a peat bed in Aldeburgh Marshes, just north of this complex, which they believe formed just above high-tide level which gave a radio-carbon date of approximately 8500 B.P.

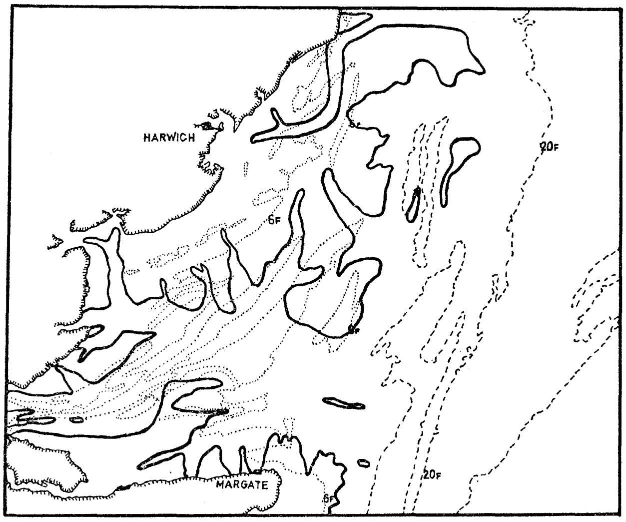

FIGURE 8. Position of the shoreline (—) about 8300 B.P.

Shoreline of 8000 B.P.

The high-tide level lay at 17 m below present-day O.D. and as such practically the whole of the present Thames Estuary was submerged. A long 'spine-land' of London Clay lay over the Wallet, Gunfleet, West Rocks, Shipwash area and stretched as far as the London Clay bank over which the present-day Shipwash Lightship is anchored. To the south the Sheppey–Cant 'spine-land' still stood above and projected out into what was now a North Sea tidal inlet, for the first time open to the full force of the North Sea tides and storms.

Since that time due to a slowly continuing sea-level rise and the still continuing subsidence of the area, the estuary has continued to enlarge. The whole of the previously mentioned Wallet–Shipwash 'spine-land' has been eroded away with the seaward projecting 18 m high cliffs of the

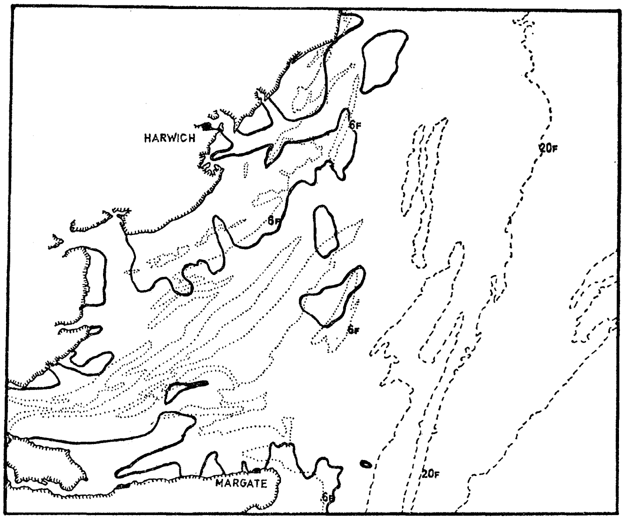

FIGURE 9. Position of the shoreline (—) about 8000 B.P.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Downloaded from rsta.royalsocietypublishing.org

Naze being all that remains of this upland, themselves being rapidly eroded by storm waves (Hails & White 1970). The lower lying areas of the Dengie Flats and Maplin Sands would have been rapidly inundated during the following centuries, receiving at first much of the sediment brought into the area by the tidal currents. The Sheppey–Cant 'spine-land' would have been rapidly eroded, as the London Clay cliffs of Sheppey are being today: more than 5 m each year at Warden Point, Sheppey (So 1963). This rate of erosion is more than adequate to account for the loss of the whole of the former extension of the Isle of Sheppey. The Isle of Thanet also has been considerably diminished in area since 8000 B.P. particularly on its more exposed eastern end. Although cliff recession here has been spasmodic since measurements have been taken, rates of between 0.3 and 9.4 m per year have been recorded (So 1965). A rate of erosion of 1.3 m per year would be sufficient to remove all the chalk to the east of the present coast over the previous 8000 years.

Subsidence and sedimentary equilibrium

Until more definitive work can be carried out into sedimentation and particularly the rate of sediment accumulation during and since this main transgressive phase, absolute values can only be tentatively established as to the rate of subsidence and eustatic change in this part of south-eastern England. One approach is to assume that a subsiding area remains in close equilibrium with its rate of sediment infill. The faster the rate of subsidence and/or rise in sea level, the faster is the rate that sediment is moved into the area. If this concept is rigidly adhered to in the Thames Estuary, the following facts emerge:

Average area of the Thames Estuary over the 9000 years a tidal system has been operative:	2000×10^9 m^2
Total volume of sediment contained in the estuary at present:	24.28×10^9 m^3
Therefore amount of sediment entering the estuary per century over the last 9000 years:	0.268×10^9 m^3
If rate of sea level rise and/or subsidence is equal to 10 cm/century then the amount of sediment needed to achieve sedimentary equilibrium is:	0.214×10^9 m^3
If rate of sea level rise and/or subsidence is equal to 12.7 cm/century then the amount of sediment needed to achieve sedimentary equilibrium is:	0.271×10^9 m^3

From this approach it would appear that there has been an average subsidence and/or sea-level rise of close to 12.7 cm (5 in) per century over the last 9000 years.

I would like to thank Dr R. J. Maddrell for reflexion profiling information and the National Environmental Research Council for financial support and for the loan of reflexion profiling equipment. Also Hunting Geology and Geophysics kindly loaned reflexion profiling equipment.

References (d'Olier)

Athy, L. F. 1930 *Bull. Am. Ass. Petrol. Geol.* **14**, 1–35.
Baak, J. A. 1936 Thesis, Leiden.
Carr, A. P. & Baker, R. E. 1968 *Trans. Inst. Br. Geogr.* **45**, 107–123.
Curray, J. R. 1961 *Bull. geol. Soc. Am.* **72**, 1707–1712.
Daly, R. A. 1920 *Geol. Mag*, **57**, 246–261.
Donn, W. L., Ferrand, W. R. & Ewing, M. 1962 *J. Geol.* **70**, 206–214.
Edelman, C. H. 1933 *Petrologische provincies in het Nederlandsche kwartair*. Amsterdam.
Fairbridge, R. W. 1962 *Quaternaria* **6**, 111–136.

Downloaded from rsta.royalsocietypublishing.org

Godwin, H. 1960 *Proc. R. Soc. Lond.* B **153**, 287–320.
Hails, J. R. & White, P. C. S. 1970 *Proc. Geol. Ass.* **81**, 205–219.
Jelgersma, S. 1961 *Mede, Geol. Stricht* C 6/7.
Kirby, R. 1969 Ph.D. Thesis, London.
Penck, A. & Bruckner, E. 1909 *Die Alpen im Eiszeitalter.* Leipzig: Tauchnitz.
Pons, L. J. & Wiggers, A. J. 1958 *Tijd. Kon. Ned. Aard. Gen.* **75**, 140–152.
Prestwich, W. H. 1850 *Q. Jl geol. Soc. Lond.* **6**, 137–265.
So, C. L. 1963 Ph.D. Thesis, London.
So, C. L. 1965 *Trans. Inst. Br. Geogr.* **37**, 147–156.
Stride, A. H. 1959 *Geol. Mag.* **96**, 33–44.
Wooldridge, S. W. & Linton, D. L. 1955 *Structure, surface and drainage in south-east England.* London: Geoffrey Philip & Son.

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF

Downloaded from rsta.royalsocietypublishing.org

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

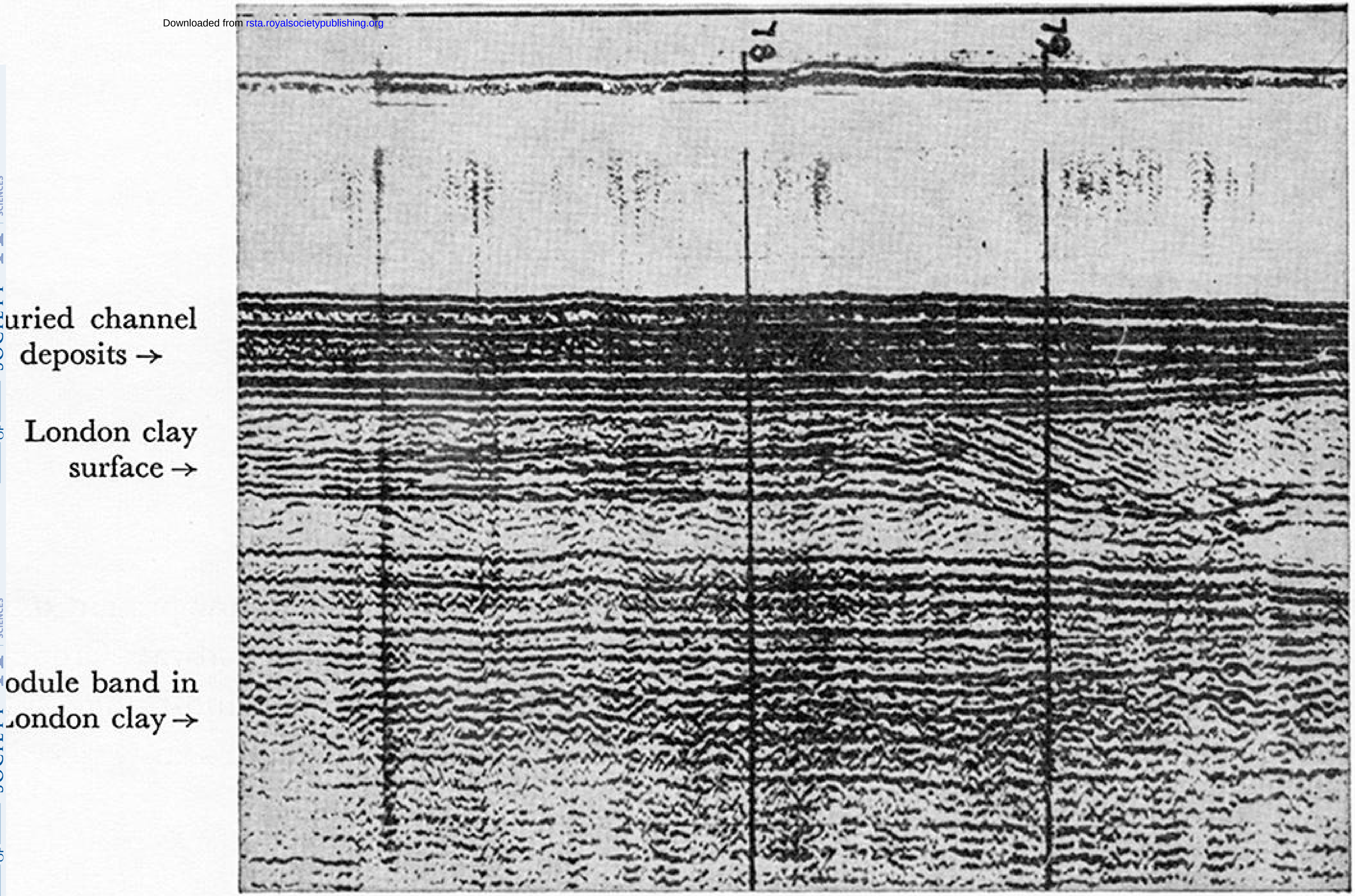

Figure 3. Continuous reflexion seismic record showing buried channel deposits.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES